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Thermal Evolution of the Phaethon–Geminid Stream Complex

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Abstract The thermal evolution of the Geminid meteor stream and the Phaethon–Geminid stream Complex (PGC) are summarized. Sodium contents of Geminid meteor streams are altered thermally, perhaps during orbital motion in interplanetary space due to the short perihelion distance of the orbit ($q \sim 0.14$ AU). However, the temperature of meteoroids is less than the sublimation temperature of Na in alkali silicates, suggesting that the parent body 3200 Phaethon itself might have suffered from the thermal processing. On the other hand, a breakup event on PGC parent is suggested by the existence of dynamically associated asteroids (Phaethon, 2005 UD and 1999 YC) sharing pristine features (C, B types). A possible mechanism behind the breakup is the sublimation of ice inside the PGC parent due to its thermal evolution. It is tempting to guess that the PGC parent might be evolved dynamically from the outer part of the main asteroid belt where the residence of ice-rich asteroids (main belt comets) into current PGC-like orbit.

Keywords Meteors · Asteroids · Comets

1 Introduction

The Apollo-type near Earth asteroid (NEA) 3200 Phaethon (1983 TB) may be a dead or dormant cometary nucleus, and is likely to be the parent body of the Geminid meteor stream because of their dynamical association (Whipple 1983). Their small perihelion distances ($q \sim 0.14$ AU) have provided possible thermal evolutional traces both on Geminid meteors and the parent body. The sodium (Na) contents of meteoroids in meteor showers are an useful indicator of their thermal evolution because Na is a moderately volatile metal element and easy to detect (Kasuga et al. 2006b). Spectroscopic studies of

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Geminid meteoroids show remarkable diversity of Na contents, from extreme depletion to Sun-like values, significantly different from trends observed in other meteor showers having larger q (Harvey 1973; Kasuga et al. 2005b; Borovička et al. 2005). As for its parent body Phaethon, the existence of the "Phaethon–Geminid stream Complex (PGC)" was suggested based on dynamical calculations (Ohtsuka et al. 2006, 2008), implying that Phaethon may have its fragments (155140) 2005 UD and 1999 YC due to breakup and split events as usually seen in cometary nuclei heated by the Sun (Chen and Jewitt 1994; Boehnhardt 2004; Jewitt 2004; Fuse et al. 2007). This short paper presents the studies of thermal evolution which had been clarified by studies of Na contents in Geminid meteor streams and the breakup of Geminid parent, leading to speculation about a possible connection to main belt comets.

2 Na Contents of Geminid Meteor Streams

Metal abundances of meteoroids in meteor showers have been revealed by spectroscopic observations (e.g. a review Ceplecha et al. 1998; Kasuga et al. 2005a, b, 2006a and references therein) and believed to show properties of their parent bodies. However, it is still unknown whether the measured values are intrinsic properties of the parent bodies. After ejection from their parent bodies into interplanetary space, the metal abundances in meteoroids may have been altered by various processes, such as thermal effects.

Kasuga et al. (2006b) investigated perihelion dependent thermal effects on meteoroids in meteor showers during orbital motion in interplanetary space after ejection from their parent bodies. The effect is supposed to alter the metal abundances from their intrinsic values in their parents, especially for temperature-sensitive elements: a good example is Na in alkali silicate. In order to clarify the dependence, three factors are considered: the temperature of meteoroids as a function of perihelion distance, the sublimation temperature of alkali silicates ($\sim$900 K) and Na abundances of meteoroids in meteor showers at each perihelion distance observed so far ($q \sim 0.14$ AU for Geminids, 0.38 AU for Taurids, 0.78 AU for Andromedids, 0.95 AU for Perseids, 0.98–0.99 AU for Leonids, Cygnids and Draconids). On orbits with $q \leq 0.1$ AU, meteoroids would show evidence of the thermal desorption of Na by the solar heating. On the other hand, Na abundances of meteoroids do not depend on their perihelion distance in the range $0.14 \leq q \leq 0.99$ AU during their orbital evolution.No Na depletion in Geminid meteoroids is to be expected because the temperature of meteoroids at $q \sim 0.14$ AU is lower than the sublimation temperature of alkali silicates. Therefore, the diversity of Na contents in Geminid meteoroids could instead originate from thermal evolution on the parent. Licandro et al. (2007) found a similarity between the reflectance spectrum of the surface of Phaethon and meteorite samples that were heated to 800–1,000 K experimentally, suggesting Phaethon's surface material could have been altered as a result of thermal processing.

3 Physical Observations for 1999 YC, 2005 UD and Phaethon

Photometry of the three candidates PGC 1999 YC, 2005 UD and Phaethon has been performed (Dundon 2005; Hsieh and Jewitt 2005; Jewitt and Hsieh 2006; Kasuga and Jewitt 2008) and their physical properties derived (see Table 1). All three Apollo-type asteroids seem to have an orbital association with the Geminid meteor stream and might be produced by the breakup of a common precursor object. If so, the colors and other physical

Table 1 Physical properties of 1999YC, 2005 UD and 3200 Phaethon

Quantity	Symbol	1999 YC[a]	2005 UD[b]	3200 Phaethon[c]
Semimajor axis	a	1.422	1.275	1.271
Perihelion	q	0.241	0.163	0.140
Eccentricity	e	0.831	0.872	0.890
Inclination	i	38.16	28.75	22.16
Color	$B-V$	0.71 ± 0.04	0.66 ± 0.03	0.59 ± 0.01
Color	$V-R$	0.36 ± 0.03	0.35 ± 0.02	0.35 ± 0.01
Color	$R-I$	–	0.33 ± 0.02	0.32 ± 0.01
Rotational period (h)	P_{rot}	4.495	5.249	3.59
Photometric range (mag)[d]	m_{R}	0.69 ± 0.05	0.40 ± 0.05	0.4
Critical density (kg m^{-3})	ρ_c	1,000	570	1,200
Mass loss rate (kg s^{-1})	$\dot{M}$	0.001	0.01	0.01
Fractional active area	f	$<10^{-3}$	$<10^{-4}$	$<10^{-5}$
Red geometric albedo	p_{R}	0.11[e]	0.11[e]	0.11 ± 0.02[f]
Absolute red magnitude (mag)	H_{R}	16.96 ± 0.03	17.13 ± 0.03	14.3 ± 0.1[f]
Equivalent circular diameter (km)	D_{e}	1.4 ± 0.1	1.3 ± 0.1	4.7 ± 0.5

Orbital data are from Ohtsuka et al. (2006) and NASA JPL HORIZON

[a] Kasuga and Jewitt (2008)

[b] Jewitt and Hsieh (2006), Kinoshita et al. (2007)

[c] Dundon (2005), Hsieh and Jewitt (2005)

[d] Peak-to-peak range of the light curve

[e] Assumed value

[f] Green et al. (1985)

properties of these objects should be similar. This is because their similar dynamical evolution would provide them with same temperature and space weathering environments. The colors of 1999 YC, 2005 UD and Phaethon indeed share primitive features of asteroids (C, B types), which are consistent with the hypothesis that they had a common parent body (see details in Jewitt and Hsieh 2006; Kasuga and Jewitt 2008).

Jewitt and Hsieh (2006) speculated on the mechanism of “ice sublimation in the core of the PGC parent”, albeit no direct clue about the breakup/split of the PGC parent body is known. Compared to the dynamical lifetime of bodies in planet-crossing orbit (10^{6-7} year) (Froeschle et al. 1995; Morbidelli et al. 2002), the shorter time scales for the heat conduction from surface to the core of the parent (10^{4-5} year) enables the ice to sublimate in the core in the PGC-like orbit. Assuming the breakup happened to the PGC parent, the pressure balance between the water vapor in the core and the hydrostatic pressure could constrain the sizes of fragments produced by the event. Any body in PGC-orbit should be smaller than 7 km in radius, which satisfied with the sizes of 1999 YC, 2005 UD and Phaethon (Table 1).

Another piece of evidence is raised comparing the total mass of Geminid meteor stream with upper limit of mass loss rate ($\dot{M}$) derived from observations of 1999 YC, 2005 UD and 3200 Phaethon shown in Table 1. That points out the contradiction that total mass of Geminids stream ($\sim 10^{12}$–10^{13} kg) (Hughes and McBride 1989; Jenniskens 1994) is much larger than total mass of the steady disintegration of PGC ($\sim 3 \times 10^{8}$ kg) (Jewitt and

Hsieh 2006; Kasuga and Jewitt 2008) if the age of stream is a few thousand years (Jones 1978; Fox et al. 1982; Jones and Hawkes 1986; Gustafson 1989; Williams and Wu 1993; Ryabova 2001; see also a review in Jenniskens 2006). At the observed mass loss rate of PGC, it is not easy to form Geminid stream within its dynamical lifetime. Therefore, the Geminid meteor streams might not be produced by steady-state disintegration of the parent, but appears to result from catastrophic breakup.

4 Connection to Main Belt Comets?

Hsieh and Jewitt (2006) found a few C-type icy-asteroids having stable orbits confined to the main asteroidal belt: the main-belt comets (MBCs). These three MBCs are distributed in the outer part of the main belt (semi-major axis of $\sim$3.2 AU) with relatively small eccentricities ($e = 0.16$–0.25).

Recently, Jewitt et al. (2009) newly discovered active MBCs (P/2008 R1) that reside in more inner part of main asteroidal belt than ever (semi-major axis of $\sim$2.7 AU, $e = 0.35$), suggesting that P/2008 R 1 is likely to originate from elsewhere in the main belt, could be outer region, and has reached its current orbits recently. The small semi-major axis of P/2008 R1 is known to be located nearby the dynamically unstable region due to the 8:3 mean-motion resonance with Jupiter, and is also affected by the secular resonance ν_6 (Yoshikawa 1987, 1988, 1989, 1990; Brož and Vokrouhlický 2008) indicated that a close correlation between the 8:3 resonance and the secular resonance ν_6 in orbital evolution of asteroids there, and found that their eccentricities may become very large, especially for asteroids in the resonance of ν_6 ($e \sim 0.8$). This region agrees quite well with the current depopulated region of asteroids, especially in the inner part of main asteroidal belt. It suggests that many bodies once there had evolved dynamically and moved to their current regions. Bottke et al. (2002) suggests that approximately 60% of all near earth objects ($H \leq 22$) could originate from the inner part of main belt, as for Phaethon as well, the region is the most likely source, although its other birth places are not ruled out yet. If MBC-like objects in the outer part of main belt were deflected through the inner part into the current PGC-orbit with small perihelion distance, it is plausible that the disruption could be caused by the sublimation of the ice in the core with the thermal processing. The object would provide fragments resulting from the breakup, such as linkage of 1999 YC, 2005 UD and Phaethon, maybe following production of meteor stream simultaneously.

A sample return mission for near earth object: MARCO POLO remarks on the primitive NEAs (C, P and D types) those source may be related with the main belt region and Jupiter family comets (Barucci et al. 2008). In addition to this view, if PGC bodies could be targets, a collisional mission like NASA's Deep Impact would help us to better understand the natures of dormant comets (ice-rich asteroids) (A'Hearn et al. 2005; Kasuga et al. 2006c). Large telescopes, such as European Extremely Large Telescope (E-ELT) (D'Odorico et al. 2008), will be required for study these faint asteroid parents, especially for spectroscopy.

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